

**PATENT**

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**PATENT APPLICATION**

**FOR**

**SYSTEM AND PROCESS FOR HEATING SEMICONDUCTOR**

**WAFERS BY OPTIMIZING ABSORPTION OF**

**ELECTROMAGNETIC ENERGY**

**OF**

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**SYSTEM AND PROCESS FOR HEATING SEMICONDUCTOR  
WAFERS BY OPTIMIZING ABSORPTION OF  
ELECTROMAGNETIC ENERGY**

**Related Applications**

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The present application is a continuation in part application of U.S. Serial No. 09/747,522, which was filed on December 21, 2001.

**Background of the Invention**

10 A thermal processing chamber as used herein refers to a device that heats objects, such as semiconductor wafers. Such devices typically include a substrate holder for holding a semiconductor wafer and an energy source, such as a plurality of lamps, that emits thermal energy for heating the wafer. During heat treatment, the semiconductor  
15 wafers are heated under controlled conditions according to a preset temperature regime. For monitoring the temperature of the semiconductor wafer during heat treatment, thermal processing chambers also typically include temperature sensing devices, such as pyrometers, that sense the radiation being emitted by the semiconductor  
20 wafer at a selected band of wavelengths. By sensing the thermal radiation being emitted by the wafer, the temperature of the wafer can be calculated with reasonable accuracy.

In alternative embodiments, instead of or in addition to using radiation sensing devices, thermal processing chambers can also  
25 contain thermocouples for monitoring the temperature of the wafers. Thermocouples measure the temperature of objects by direct contact.

Many semiconductor heating processes require a wafer to be heated to high temperatures so that various chemical and physical reactions can take place as the wafer is fabricated into a device. During  
30 rapid thermal processing, which is one type of processing,

semiconductor wafers are typically heated by an array of lights to temperatures, for instance, from about 400°C to about 1,200°C, for times which are typically less than a few minutes. During these processes, one main goal is to heat the wafers as uniformly as possible.

5 Problems have been experienced in the past, however, in being able to maintain a constant temperature throughout the wafer and in being able to control the rate at which the wafer is heated. If the wafer is heated nonuniformly, various unwanted stresses can develop in the wafer. Not being able to heat the wafers uniformly also limits the ability  
10 to uniformly deposit films on the wafers, to uniformly anneal films on the wafers, besides limiting the ability to perform various other chemical and physical processes on the wafers.

Some of the problems that have been experienced in the past relate to the fact that semiconductor wafers are frequently coated with  
15 films of materials that affect the reflectivity and absorptivity of the surface. For instance, there can be variations between different wafers, and there can also be variations within a single wafer as a result of patterns produced on the wafer during the semiconductor device fabrication sequence. When wafers are irradiated by electromagnetic  
20 radiation, these variations in optical properties result in variations in the ability of the wafer to absorb power and consequent variations in the temperature reached. This can degrade the repeatability of thermal processing and can also degrade the uniformity across any given wafer. For example, a wafer with different regions coated with different  
25 materials will have different power absorption characteristics in these regions.

As such, a need currently exists for an improved thermal processing chamber and process that is capable of more efficiently heating semiconductor wafers and that is capable of uniformly heating

semiconductor wafers.

### **Summary of the Invention**

The present invention is generally directed to various processes for heating semiconductor wafers. In particular, the present invention is directed to configuring light sources emitting light energy onto the wafer in order to optimize absorption of the energy by the wafer. The present invention is carried out by varying the angle of incidence of the light energy contacting the wafer, using multiple wavelengths of light, and configuring the light energy such that it contacts the wafer in a particular polarized state.

For example, in one embodiment of the present invention, the process includes the steps of placing a semiconductor wafer in a processing chamber. Light energy is directed onto the wafer for heating the wafer. The light energy contacts the wafer at an angle of incidence of greater than  $0^\circ$ . Particularly, the angle of incidence is greater than  $10^\circ$ , and more particularly from about  $40^\circ$  to about  $85^\circ$ .

The process further includes the step of polarizing the light energy prior to the light energy contacting the semiconductor wafer. In particular, the light energy is polarized such that the light energy contacts the semiconductor wafer in a p-polarized state. Any suitable polarizing device can be used to polarize the light. For example in one embodiment, a beam splitting device can be used that creates a first p-polarized light energy beam and a second p-polarized light energy beam. The first and second p-polarized light energy beams are then directed onto the semiconductor wafer. In still a further alternative embodiment of the present invention, the light energy is polarized using a wire-grid polarizing device.

The light energy used in accordance with the present invention can be emitted from a laser or from an incoherent light source. When

using an incoherent light source, such as an arc lamp or a tungsten halogen lamp, the light can be collimated prior to being polarized.

In an alternative embodiment of the present invention, the process includes the steps of placing a semiconductor wafer in a processing chamber and directing laser beams onto the semiconductor wafer from at least a first laser and a second laser. The first laser emits light at a first wavelength range and the second laser emits light at a second wavelength range. In order to heat the wafer more uniformly and efficiently, the first wavelength range is different from the second wavelength range.

Besides or in addition to using laser beams at different wavelength ranges, the beams can contact the wafer at different angles of incidence. In particular, each beam should contact the semiconductor wafer at an angle of incidence greater than  $10^\circ$ , in particular at an angle of incidence from about  $40^\circ$  to about  $85^\circ$ . When using laser beams to heat semiconductor wafers, the laser beams can be configured to strike the wafer in a particular state, such as a p-polarized state.

In one particular embodiment of the present invention, which is particularly well suited to carry out an ion implantation anneal process, the method of the present invention includes placing a semiconductor wafer in a thermal processing chamber. A pulsed laser beam is then directed onto the semiconductor wafer. The pulsed laser beam is configured to strike the wafer at an angle of incidence of at least  $10^\circ$  and in a particular state, such as a p-polarized state.

Light energy sources configured in accordance with the present invention can be used alone to heat wafers or can be used in conjunction with other energy sources. For instance, the light energy sources of the present invention can be used in conjunction with other light energy sources and/or in conjunction with a susceptor plate.

Other features and aspects of the present invention are discussed in greater detail below.

### **Brief Description of the Drawings**

A full and enabling disclosure of the present invention, including  
5 the best mode thereof, directed to one of ordinary skill in the art, is set forth more particularly in the remainder of the specification, which makes reference to the appended figures in which:

Figure 1 is a cross-sectional view of one embodiment of a thermal  
10 processing chamber that may be used in accordance with the present invention.

Figure 2 is a diagrammatical plan view in accordance with the  
present invention showing a plurality of lamps positioned above a  
semiconductor wafer and having an angle of incidence with the wafer of  
greater than  $0^\circ$ .

15 Figure 3 is an informational diagram provided to illustrate several terms to be used in the present application.

Figure 4 is a graph showing the spectral absorptivity of a  
semiconductor wafer having a bottom coating of silicon dioxide and a top  
coating of polysilicon. The curves are shown for a  $45^\circ$  angle of incidence  
20 for p-polarized radiation, s-polarized radiation and unpolarized radiation.

Figure 5 is a graph showing the spectral absorptivity for the same  
structure as in Figure 4. In this figure, however, the curves are for p-  
polarized radiation at different angles of incidence.

Figure 6 is a side view illustrating a laser emitting a laser beam  
25 onto a semiconductor wafer at an angle of incidence greater than  $0^\circ$ .

Figure 7(a) is a side view of two different lasers emitting laser  
beams onto a semiconductor wafer at different angles of incidence.

Figure 7(b) is a side view of a laser beam being split into two different beams that contact a semiconductor wafer at two different angles of incidence.

Figure 8 is a side view of an incoherent light source in which light emitted from the light source is collimated and then polarized contacting a wafer at an angle of incidence greater than  $0^\circ$ .

Figure 9 is an alternative embodiment of the process shown in Figure 8, in which the polarizing device splits the light into two different p-polarized radiation beams.

Repeat use of reference characters in the present specification and drawings is intended to represent same or analogous features or elements of the invention.

#### **Detailed Description of the Preferred Embodiments**

It is to be understood by one of ordinary skill in the art that the present discussion is a description of exemplary embodiments only, and is not intended as limiting the broader aspects of the present invention, which broader aspects are embodied in the exemplary construction.

A thermal processing apparatus uses thermal energy, such as intense light, to heat a semiconductor wafer as part of the manufacturing process of integrated circuits. Exposure to light energy causes a rapid increase in the temperature of a semiconductor wafer and allows processing times to be relatively short. In rapid thermal processing systems, it is important to radiate the wafer with very high intensity light in a very uniform and controlled fashion. As stated above, the difficulty with current devices is that the requirements for the intensity of the radiated light and the ability to heat wafers uniformly are very difficult to achieve.

For instance, semiconductor wafers are frequently coated with materials that affect the reflectivity and the absorptivity of the surface.

These coatings contained on the wafers can lead to inefficiencies in heating the wafers and can also lead to temperature variations within the wafer. For example, a wafer having regions coated with different materials will have different power absorption characteristics in these regions.

In general, the present invention is directed to an apparatus and method for heating semiconductor wafers uniformly and efficiently. Wafers processed according to the present invention are heated, at least partly, by light energy. The present invention is directed to optimizing the angle of incidence, the plane of polarization and the wavelengths of the heating radiation in order to increase the absorptivity of the wafer and to decrease the effects of variations in the optical properties of the surfaces of the wafer.

More particularly, the present invention is directed to placing lamps in a thermal processing chamber for heating objects, such as semiconductor wafers. The lamps are configured so that the light energy being emitted by the lamps contacts the wafer at an angle of incidence that optimizes absorption by the wafer. Alternatively, or in addition to optimizing the angle of incidence, the light energy being emitted by the lamp can also be configured such that the light energy contacts the wafer in a plane of polarization that also optimizes absorption. Finally, the present invention is also directed to contacting the wafer with multiple wavelengths of light so that at least certain of the wavelengths are being efficiently absorbed by the wafer.

Referring to figure 3, a diagram is shown that illustrates some definitions and terms used in the present application. As shown, the angle of incidence,  $\theta$ , is the angle between the normal to the wafer surface and direction of propagation of the heating radiation. The plane of incidence is the plane that contains the normal to the wafer surface



and the ray of energy incident on the wafer surface. The p-polarization plane is the polarization state where the electric field vector of the incident radiation lies in the plane of incidence. This state is also known as the transverse magnetic (TM) polarization. The polarization at right  
5 angles to the p-polarization state, where the electric field vector is perpendicular to the plane of incidence, is known as the s-polarization state or the transverse electric (TE) polarization state.

The lamps that can be used in accordance with the present invention can vary depending upon the particular application. For  
10 instance, in one embodiment, lasers can be used. Lasers emit light over a very narrow wavelength range. Besides lasers, various incoherent light sources can also be used in the system of the present invention. Incoherent light sources as opposed to lasers, emit light over a broad range of wavelengths. Incoherent light sources that can be used in the  
15 present invention include arc lamps, tungsten halogen lamps, and the like.

Lamps configured according to the present invention can be used alone to heat semiconductor wafers or, alternatively, can be used in conjunction with other thermal energy sources. For instance, the lamps  
20 can be used in conjunction with a susceptor or hot plate, which heats wafers through electrical resistance. In another embodiment, the lamps configured according to the present invention can be used in conjunction with other lamps that are not specially configured.

Referring to figure 1, one embodiment of a system generally 10  
25 made in accordance with the present invention is shown. In this embodiment, the system includes a plurality of lamps 40 configured in accordance with the present invention and a plurality of other lamps 24 that are placed over a semiconductor wafer 14 as is conventional in the art.

As shown, system 10 includes a processing chamber 12 adapted to receive substrates such as a wafer 14 for conducting various processes. Wafer 14 can be made from a semiconductive material, such as silicon. As shown, wafer 14 is positioned on a substrate holder 15 made from a thermal insulating material such as quartz. Chamber 12 is designed to heat wafer 14 at very rapid rates and under carefully controlled conditions. Chamber 12 can be made from various materials, including metals and ceramics. For instance, chamber 12 can be made from stainless steel or can be a cold wall chamber made from, for instance, quartz.

When chamber 12 is made from a heat conductive material, preferably the chamber includes a cooling system. For instance, as shown in Figure 1, chamber 12 includes a cooling conduit 16 wrapped around the perimeter of the chamber. Conduit 16 is adapted to circulate a cooling fluid, such as water, which is used to maintain the walls of chamber 12 at a constant temperature.

Chamber 12 can also include a gas inlet 18 and a gas outlet 20 for introducing a gas into the chamber and/or for maintaining the chamber within a preset pressure range. For instance, a gas can be introduced into chamber 12 through gas inlet 18 for reaction with wafer 14. Once processed, the gas can then be evacuated from the chamber using gas outlet 20.

Alternatively, an inert gas can be fed to chamber 12 through gas inlet 18 for preventing any unwanted or undesirable side reactions from occurring within the chamber. In a further embodiment, gas inlet 18 and gas outlet 20 can be used to pressurize chamber 12. A vacuum can also be created in chamber 12 when desired, using gas outlet 20 or an additional larger outlet positioned beneath the level of the wafer.

During processing, substrate holder 15, in one embodiment, can be adapted to rotate wafer 14 using a wafer rotation mechanism 21. Rotating the wafer promotes greater temperature uniformity over the surface of the wafer and promotes enhanced contact between wafer 14 and any gases introduced into the chamber. It should be understood, however, that besides wafers, chamber 12 is also adapted to process optical parts, films, fibers, ribbons, and other substrates having any particular shape.

A heat source or heating device generally 22 is included in communication with chamber 12 for heating wafer 14 during processing. Heating device 22 includes a plurality of linear lamps 24, such as tungsten-halogen lamps. As used herein, a "linear lamp" refers to a lamp that is designed to emit most of its energy through the longest dimension of the lamp. For instance, in most embodiments, linear lamps emit the majority of their energy through the side of the lamp. As shown in Figure 1, lamps 24 are horizontally aligned above wafer 14. It should be understood, however, that lamps 24 may be placed at any particular location such as only below the wafer or above and below the wafer. Further, additional lamps could be included within system 10 if desired.

Besides linear lamps, the system of the present invention can also use vertically oriented lamps. These lamps are positioned such that the end of the lamp faces the wafers.

As shown in the figure, lamps 24 are equipped with a gradual power controller 25 that can be used to increase or decrease the light energy being emitted by any of the lamps.

In order to assist in directing the light energy being emitted by lamps 24 onto wafer 14, the lamps can be associated with a reflector or a set of reflectors. For instance, as shown in Figure 1, the heating device 22 includes a reflector plate 36 positioned above the linear lamps

24. Reflector plate 36 can be made from any material suitable for reflecting light energy and can have any suitable shape that will assist in directing the light energy toward the wafer 14.

In addition to lamps 24, as shown in Figure 1, the system includes  
5 light sources or lamps 40 in accordance with the present invention. As shown, lamps 40 are positioned with respect to the wafer 14 at an angle in order to optimize absorption of light energy by the wafer. As will be described in more detail below, besides adjusting the angle of incidence, radiation emitted by lamps 40 can also be configured to strike the wafer  
10 in or near the p-polarization plane.

As shown in Figure 1, lamps 40 configured in accordance with the present invention can be used in conjunction with lamps 28.  
Alternatively, as shown in Figure 2, wafer 14 can be heated solely by  
lamps 40. In particular, as shown in Figure 2, lamps 40 are positioned  
15 surrounding the wafer 14 at desired angles.

In a still further embodiment of the present invention, lamps 40 can be used in conjunction with a susceptor that is placed adjacent to the wafer. The susceptor can include an electrical resistance heater for heating the wafer.

Referring to Figure 1, in order to monitor the temperature of wafer  
20 14 during the heating process, in this embodiment, thermal processing chamber 12 includes plurality of radiation sensing devices generally 27. Radiation sensing devices 27 include a plurality of optical fibers or light pipes 28 which are, in turn, in communication with a plurality of  
25 corresponding light detectors 30. Optical fibers 28 are configured to receive thermal energy being emitted by wafer 14 at a particular wavelength. The amount of sensed radiation is then communicated to light detectors 30 which generate a usable voltage signal for determining the temperature of the wafer which can be calculated based, in part, on

Planck's Law. In one embodiment, each optical fiber 28 in combination with a light detector 30 comprises a pyrometer. In another embodiment, the optical fibers 28 are routed to a single but multiplexing radiation sensing device.

5           In general, thermal processing chamber 12 can contain one or a plurality of radiation sensing devices. In a preferred embodiment, as shown in Figure 1, thermal processing chamber 12 contains a plurality of radiation sensing devices that measure the temperature of the wafer at  
10       locations can then be used to control the amount of heat being applied to the wafer as will be described in more detail hereinafter. The amount of heat applied to various zones of the wafer can also be controlled in an open loop fashion. In this configuration the ratios between the various heating zones can be pre-determined after manual optimization.

15           System 10 further includes a window 32 which separates lamps 24 from the chamber. Window 32 serves to isolate lamps 24 from wafer 14 and prevent contamination of the chamber. Window 32 as shown in Figure 1 can be a window positioned between chamber 12 and heat source 22.

20           Besides using radiation sensing devices, other temperature sensing devices may be used in the system of the present invention. For instance, one or more thermocouples may be incorporated into the system for monitoring the temperature of the wafer at a single location or at a plurality of locations. The thermocouples can be placed in direct  
25       contact with the wafer or can be placed adjacent the wafer from which the temperature can be extrapolated.

          System 10 further includes a system controller 50 which can be, for instance, a microprocessor. Controller 50 receives voltage signals from light detectors 30 that represent the radiation amounts being

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sampled at the various locations. Based on the signals received, controller 50 is configured to calculate the temperature of wafer 14 at different locations.

System controller 50 as shown in Figure 1 can also be in  
5 communication with lamp power controller 25. In this arrangement, controller 50 can determine the temperature of wafer 14, and, based on this information, control the amount of thermal energy being emitted by lamps 24 and/or lamps 40. In this manner, instantaneous adjustments can be made regarding the conditions within reactor 12 for processing  
10 wafer 14 within carefully controlled limits.

In one embodiment, controller 50 can also be used to automatically control other elements within the system. For instance, controller 50 can be used to control the flow rate of gases entering chamber 12 through gas inlet 18. As shown, controller 50 can further be  
15 used to control the rate at which wafer 14 is rotated within the chamber.

As described above, the present invention is generally directed to configuring various light sources in thermal processing chambers in order to optimize absorption of light energy by the wafer being heated. It is the intent of the present invention to minimize problems experienced in  
20 the past when processing wafers having different properties and/or being coated with different materials. In general, the present invention is directed to changing the angle of incidence of the light sources to maximize absorption, configuring the light emitted by the light sources to be placed in the p-polarized state or substantially in the p-polarized state  
25 in order to optimize absorption and/or to use several different wavelengths in order to ensure that at least some of the light energy is being efficiently absorbed by the wafer.

Figures 4 and 5 are intended to illustrate some of the concepts involved with respect to the present invention. Figure 4 illustrates the

spectral absorptivity of a semiconductor wafer that is coated with a two-layered coating. The two-layered coating includes a bottom coating of silicon dioxide and a top coating of polysilicon. Specifically, the bottom coating of silicon dioxide was 0.5 microns thick, while the top coating of polysilicon was 0.2 microns thick. The graph illustrated in Figure 4 shows how absorption changes with wavelength. Further, the graph includes three curves representing the absorptivity for light energy contacting the wafer at an angle of incidence of  $45^\circ$  for the three cases of the light energy being in the (1) p-polarized state, (2) s-polarized state, and (3) unpolarized state. As shown, the unpolarized state becomes the average of the s-polarized and p-polarized states.

As shown in Figure 4, the amount of variation in spectral absorptivity is reduced by contacting the wafer with light energy in the p-polarized state. Further, at any given wavelength the absorptivity is greater for the p-polarized light, which indicates better and more efficient power coupling.

Figure 5 illustrates the spectral absorptivity of the same structure used to produce the results illustrated in Figure 4. In the graph illustrated in Figure 5, however, all of the curves represent light energy in the p-polarized state. In this graph, the angle of incidence varies between normal ( $0^\circ$ ),  $45^\circ$  and  $60^\circ$ .

As shown, the variations in spectral absorptivity are reduced as the angle of incidence rises from  $0^\circ$  to  $60^\circ$ . Further, increased absorptivity can be seen at different wavelengths depending upon the angle of incidence.

In accordance with the present invention, Figures 4 and 5 show that various benefits can be realized if (1) multiple wavelengths of light are used, (2) the light is configured in the p-polarized state and (3) the angle of incidence is increased to greater than  $0^\circ$ . Further, Figure 5 also

illustrates the potential benefit of arranging the lamps at more than one angle of incidence for further optimizing absorption.

Referring to Figures 6 through 9, various applications of the present invention will now be discussed in detail. Figures 6 and 7 are particularly directed to the use of lasers for heating semiconductor wafers, while Figures 8 and 9 are directed to applying the concepts of the present invention to incoherent light sources.

Referring to Figure 6, a laser 40 is shown emitting a laser beam 60 onto a wafer 14 at an angle of incidence 2. In general, lasers emit light over a relatively narrow wavelength range. Lasers can be very effective heating devices providing light at a very high intensity. Because of the highly monochromatic nature of laser radiation, however, there is effectively very little spectral averaging of power absorption by the wafer, which makes laser heating especially susceptible to power absorption fluctuations during a single heating cycle for a semiconductor wafer and during the processing of different wafers.

As shown in Figure 6, absorption fluctuations can be minimized by changing the angle of incidence of the laser beam 60. As described above, the reflectivity of most surfaces is a function of the angle of incidence. Thus, changing the angle of incidence of the laser light contacting the wafer can increase absorption:

For most applications, when processing semiconductor wafers, optimization of absorption occurs when the angle of incidence is greater than  $10^\circ$ , such as from about  $40^\circ$  to about  $85^\circ$  and more particularly from about  $60^\circ$  to about  $85^\circ$ . In particular, the reflectivity of silicon is very low near a critical angle, i.e. the Brewster angle. For silicon, the Brewster angle is approximately  $75^\circ$ .

Of particular advantage when using lasers is that not only is the radiation highly directional, but many types of laser light are naturally



plane-polarized. Consequently, when adjusting the angle of incidence, the laser beam can also be placed in the p-polarized plane with respect to the wafer surface. As shown in Figures 4 and 5 above, optimization of light coupling to the wafer can occur when placing the light in the p-

5 polarized state.

If should be understood, however, that besides placing the light in the p-polarized state, in other embodiments, it may be preferred to place the light in other configurations. For example, in an alternative embodiment, the light can be placed not in the p-polarized state, but near

10 the p-polarized state. In an alternative embodiment, elliptically polarized light can be directed towards the wafer. Elliptically polarized light refers to polarization of an electromagnetic wave in which the electric field vector at any point in space describes an ellipse in a plane perpendicular to the propagation direction.

15 The particular light configuration used in any application will depend on various factors. For instance, the topography of the surface being heated can play a role in determining how the light contacting the wafer should be configured. Trenches, angles, and other non-smooth features of a surface, for example, can have an impact upon the

20 absorption characteristics of the wafer. When dealing with a substrate having a 3-dimensional surface, in one embodiment, a planar surface can be defined that best takes into account the surface irregularities. Once the planar surface is defined, the polarization, the angle of incidence, and the wavelength of light to contact the surface can be

25 selected.

Various methods can be used in order to orient the laser device for ensuring that the laser beam 60 strikes the wafer 14 in the p-polarized plane or in some other desirable configuration. For example, in order to adjust the laser beam into the p-polarized state, the laser can be

rotated or the laser beam can be manipulated using mirrors and/or optics. In one embodiment, for instance, a half wave plate can be used to place the laser beam into a defined plane, such as a p-polarization plane.

5           Alternatively or in addition to adjusting the angle of incidence and placing the laser beam in a p-polarized state, several different types of lasers can be used in the thermal processing chamber that each emit light at different wavelengths. For instance, as shown in Figure 7(a) a first laser 40 and a second laser 140 can emit light at different  
10           wavelengths onto the wafer 14.

          Thus, when a particular substrate is highly reflective at the wavelength at which one laser operates, the second laser operating at a different wavelength can be used to heat the wafer. The radiation from the different lasers may be optically combined before contacting the  
15           wafer. Alternatively, several beams of light from the different lasers could illuminate a selected area of the wafer. In still another alternative embodiment, several beams of light could irradiate the same wafer radius as the wafer is rotated. The lasers can be arranged to illuminate the front and/or back of the wafer. Also, in one embodiment, the front of  
20           the wafer can be heated at a particular wavelength or range of wavelengths, while the back of the wafer can be heated by light at a different wavelength or range of wavelengths.

          In one embodiment of the present invention, adjustable lasers can be used in order to heat the wafer. For example, lasers can be used that  
25           have an adjustable wavelength setting for adjusting the wavelength during a particular heating cycle or from heating cycle to heating cycle. Besides adjusting the wavelength, lasers used in the present invention can also be moveable for adjusting the angle of incidence during processing. In this manner, optimum power coupling between the light

sources and the wafer can occur as the characteristics and properties of the surface of the wafer being heated changes.

Besides using lasers which operate at different wavelengths, as shown in Figure 7(a), the angle of incidence of each laser 40 and 140 can be different so as to ensure that at least one of the lasers will have a high degree of absorption during the heating process.

Multiple angles of incidence can be created using multiple lasers as shown in Figure 7 (a) or can be implemented using a single laser as shown in Figure 7(b). As shown in Figure 7(b), laser 40 emits a laser beam 60 which is broken into two beams 62 and 64 by a beam splitting device 70. In this embodiment, a mirror 72 is then used to direct laser beam 64 onto the wafer 14 at an angle of incidence that is different than the angle of incidence of laser beam 62. Besides a mirror 72, however, it should be understood that the laser beam can be directed onto the wafer using, for instance, fiber optics, lenses, light pipes, and the like.

In general, any suitable type of laser can be used in the present invention including both continuous wave lasers and pulsed lasers. In one embodiment, a laser diode is used. Laser diodes efficiently convert electricity into laser radiation and are available in high power ratings. For example, high power devices, delivering continuous power of greater than 10 watts are currently commercially available, with emission wavelengths between 400 nm and 4000 nm. The above described lasers can be combined with beam delivery optics that reshape the emitted beam and direct it to the wafer. For example, the laser can be coupled with fiber optics for guiding the light onto a particular location of the wafer.

In one particular embodiment of the present invention, it has been discovered that the use of pulsed lasers may provide various advantages. Pulsed lasers produce high quantities of energy

intermittently. Such lasers may be particularly well suited for use in anneal processes, particularly ion implantation damage anneal processes. It is believed that pulsed lasers can provide controlled damage annealing for producing films having superior qualities.

5           As described above, lasers emit highly directional light. In order to heat the entire surface of a semiconductor wafer using lasers, various techniques can be used. For instance, in one embodiment, a plurality of lasers can be positioned within the thermal processing chamber to contact different areas of the wafer. If desired, the laser beams being  
10           emitted by the lasers can also be shaped using optics, as long as shaping the beam does not interfere with the optimization techniques described herein. Alternatively, the laser beam can be scanned over the entire surface of the wafer or over a selected region.

          Besides configuring laser beams, the present invention is also  
15           applicable to light beams emitted by incoherent light sources, such as tungsten halogen lamps or arc lamps. The light sources can emit continuous light or pulsed light. Incoherent light sources typically emit light energy over a broader spectrum than lasers. As a result, less variations in power coupling occur when using incoherent light sources  
20           due to a larger range of wavelengths and normally a wider range of angles of incidence. Nevertheless, the present invention can be used to further improve power coupling between incoherent light sources and a wafer being heated.

          For example, in one embodiment, light being emitted by an  
25           incoherent light source can be collimated, polarized and configured to strike the wafer at an angle of incidence greater than  $0^\circ$ , particularly greater than  $10^\circ$  in accordance with the present invention.

          For instance, referring to Figure 8, an incoherent light source 40 is shown emitting light energy onto the wafer 14. The incoherent light

source 40 can be, for instance, an arc lamp, a tungsten halogen lamp, and the like. As shown in the figure, light emitted from lamp 40 is collimated using a reflector 80 so that most of the light strikes the wafer 14 at a particular angle of incidence.

5           Reflector 80 surrounds the light source 40 and can have various shapes. In general, however, a parabolic shape as shown will create a collimated output beam.

          Besides using a reflector, various other devices can be used to collimate the light being emitted by the lamp 40. For instance, an  
10       alternative embodiment, optical lenses can be used to better direct the light onto the wafer. For instance a converging lens, a cylindrical lens or a zone plate can be used alone or in combination with reflectors in order to collimate the light.

          Besides collimating the light being emitted by the lamp 40, as  
15       shown in Figure 8, the system of the present invention can further include a polarizing device 82. Polarizing device 82 is selected so that light exiting the polarizing device is in the p-polarized state. As a result of this configuration, light energy being emitted by the lamp 40 strikes the wafer 14 at a desired angle of incidence and in the p-polarized state for  
20       optimizing absorption by the wafer.

          Besides placing the light in the p-polarized state, polarizing device 82 can also be used to place the light in a near p-polarized state or can be used to create elliptically polarized light as desired.

          Many polarizing devices 82 as shown in Figure 8, however, can  
25       significantly decrease the amount of light energy that reaches the wafer. For instance, some polarizing devices eliminate up to about 50% of the energy being emitted by the lamp 40. In order to more efficiently polarize the light being emitted from the lamp 40, in an alternative embodiment, a polarizing beam splitting device 84 can be used as shown in Figure 9.

Polarizing beam splitting device 84 receives the collimated light being emitted by lamp 40 and splits the light into two beams 90 and 92.

Polarizing beam splitting device 84 is configured such that beam 90 is in the p-polarized state. As shown, beam 90 contacts the wafer 14 at a first  
5 angle of incidence.

Beam 92, on the other hand, is then further redirected using a mirror, optics, a half wave plate, or other suitable optic device 86. Specifically, light beam 92 is rotated, oriented or otherwise manipulated and redirected onto the wafer 14 as light beam 94 in the p-polarized  
10 state or in some other desired configuration at a second angle of incidence. The angle of incidence of beam 90 and 94 can be the same or can be different.

Various different polarizing devices may be used in the present invention. Polarizing beam splitting device 84, for instance, can be a  
15 wire grid polarizer, a thin film coated device such as a dielectric film coated device, a cube beam splitter, or any other suitable device.

Referring back to Figure 1, as described above, the system of the present invention can include a controller 50. Controller 50 can be used to monitor the temperature of the wafer and control the amount of light  
20 energy being emitted onto the wafer accordingly. In one embodiment of the present invention, the controller 50 can be placed in communication with one or more sensors 98. Sensors 98 can be used to detect the amount of radiation that is being reflected from the wafer. Specifically, the sensors can help estimate the amount of power reflected in order to  
25 adjust the input power being delivered to the wafer. Sensors 98 would be particularly applicable in a system using laser illumination, where a simple estimate of the coupling could be obtained from the reflected beam intensity. This estimate could be obtained before processing, using a lower power beam, or during processing from the actual beam.

Besides changing the amount of power delivered to the wafer, information collected from the sensors can also be used to change the wavelength of light contacting the wafer and/or to change the angle of incidence of the light contacting the wafer.

- 5           Sensors 98 can be any suitable device capable of detecting reflected light. For example, sensors 98 can be photo detectors or thermal detectors.

- 10           In still a further embodiment of the present invention, the system can include reflectors positioned in the thermal processing chamber. The reflectors can be used to reflect light energy being reflected from the wafer back onto the wafer. Again, such reflectors would be particularly well suited for use in systems using laser beams. An example of a reflector that may be used is a corner cube retro reflector, which would send light being reflected from the wafer back onto the wafer at the same angle of reflection. By reflecting the light back onto the wafer, further light energy will be absorbed by the wafer during heating.

- 15           In still another embodiment of the present invention, the techniques and advantages of the present invention can be used to heat not only the wafer 14, but a slip free ring 99 as shown in Figure 1. A slip free ring refers to a device that completely encircles or at least substantially surrounds the edges of a wafer and provides further energy to heat the edges of the wafer during processing. Slip free rings are generally used to counteract heat losses that occur at the wafer's edge.

- 20           In accordance with the present invention, slip free ring 99, as shown in Figure 1, can be heated by the light devices 40 in a manner that optimizes thermal coupling. For instance, the light devices 40 can emit light at a particular angle of incidence and in a particular polarized state for optimizing the amount of thermal energy that is absorbed by the slip free ring 99. The particular angle of incidence, light wavelength, and

polarized state of the light that heats the slip free ring will depend upon the material from which the slip free ring is made. For instance, the slip free ring can be made from various materials including silicon, silicon carbide, graphite, silicon carbide coated graphite, quartz, besides  
5 various other materials.

In accordance with the present invention, the slip free ring 99 can also be coated with various materials in order to optimize light absorption. For instance, the slip free ring can be coated with anti-reflective coatings. For example, in one embodiment, a silicon ring can  
10 be coated with silicon dioxide or silicon nitride.

These and other modifications and variations to the present invention may be practiced by those of ordinary skill in the art, without departing from the spirit and scope of the present invention, which is more particularly set forth in the appended claims. In addition, it should  
15 be understood that aspects of the various embodiments may be interchanged both in whole or in part. Furthermore, those of ordinary skill in the art will appreciate that the foregoing description is by way of example only, and is not intended to limit the invention so further described in such appended claims.

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